New tools for detection of "macroscopic" dark matter

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Based on:

E. Hall, T. Callister, V. Frolov, H. Muller, MP, R. Adhikari, 1606.01103 "Laser Interferometers as Dark Matter Detectors"

Related ideas in

MP et al, 1205.6260, PRL 2013

A. Derevianko and MP, 1311.1244, Nature Phys 2014

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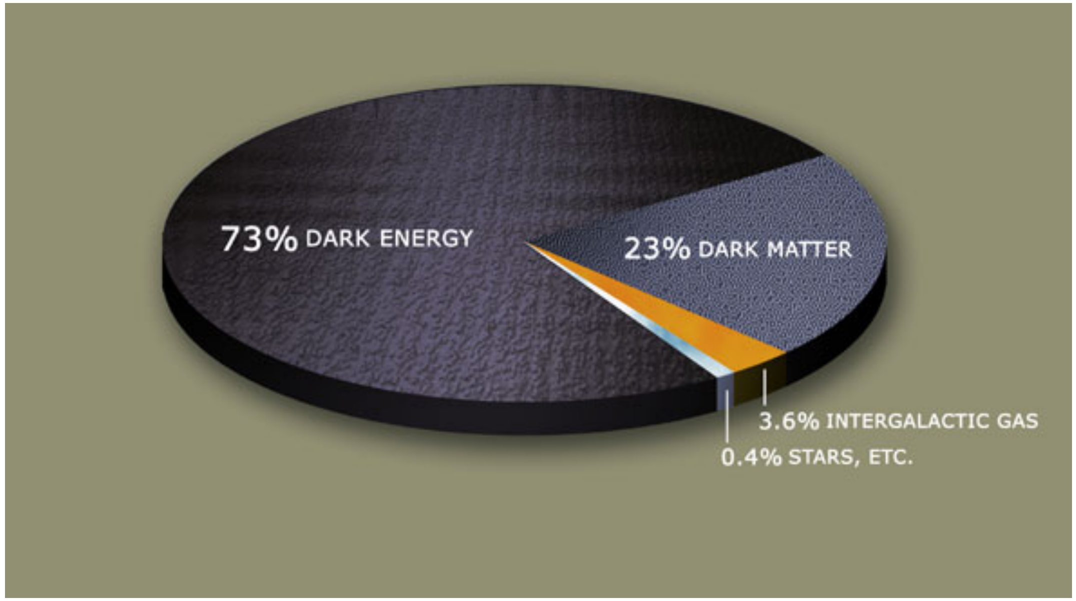
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. *Introduction. Many types of dark matter [all good].*
2. Light fields, and a possibility of coherent long range interactions
3. Macroscopic size dark matter with advanced Ligo, and future detectors.
4. Networks of atomic clocks and magnetometers.
5. Conclusions.

Big Questions in Physics



"Missing mass" – what is it?

New particle, new force, …? *So far, DM presence is only detected through gravitational interactions*

Challenges ?? Too many options for DM. In "direct detection" there is an extrapolations from ~ kpc scale (~ 10^{21} cm) down to 10^2 cm scale.

Classification of particle DM models

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. (asymmetric WIMPs are a variation.)

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **super-WIMPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Many reasonable options. *Signatures can be completely different.*

Macroscopic DM? Primordial Black holes, of course. But this is not the only possibility. Topological and non-topological solitons etc. What are possible signatures?

WIMP "lamp post"

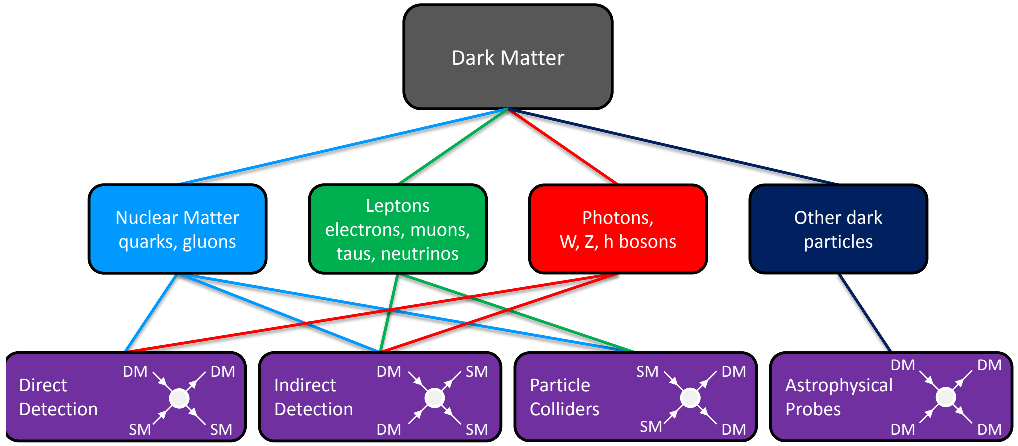
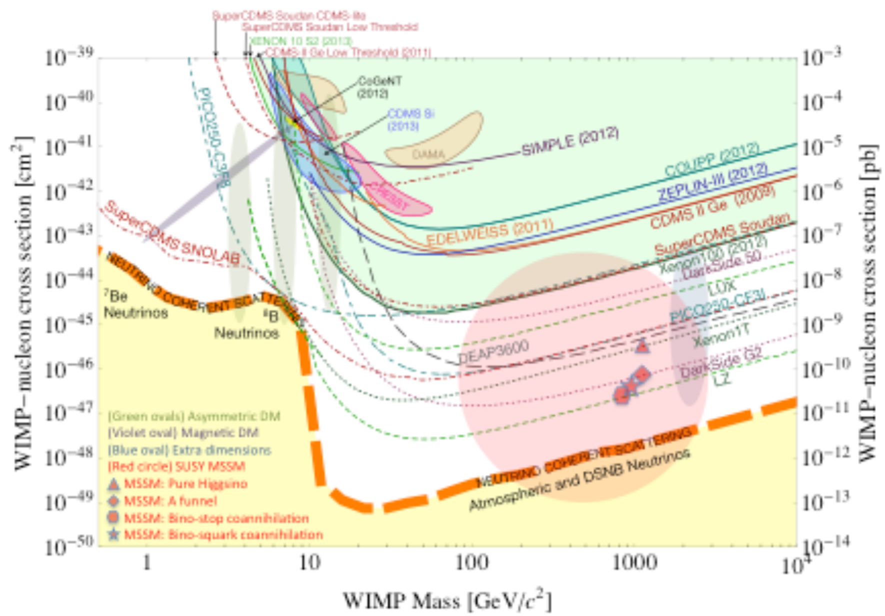


Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*



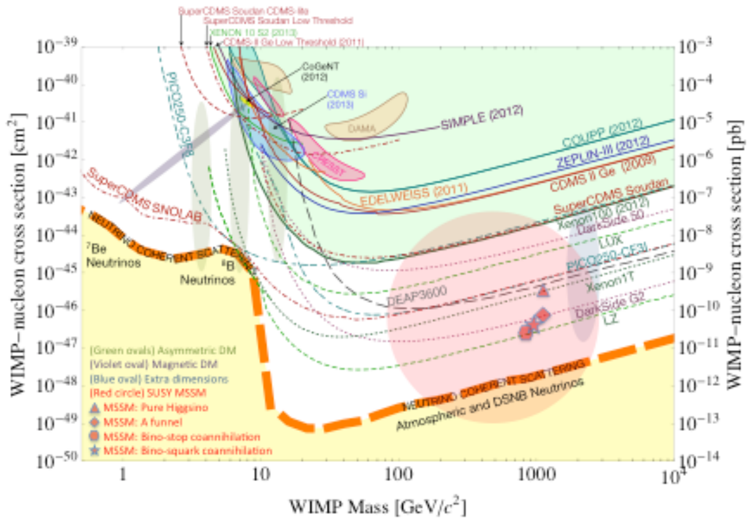
From the Snowmass 2013 summary, 1310.8327

New lampposts in DM searches

- WIMP dark matter outside of the "usual" mass range.
- Bosonic Dark Matter with precision measurements.
- Macroscopic dark matter (?)

With 50 orders of magnitude mass span just for particle DM, there got to be additional "windows of opportunity" for DM searches

How sensitive are WIMP experiments to gravitational interaction ?



$\sigma_{DM\text{-}N} \sim (G_N m_N m_{DM})^2 / (\mu^2 v^4) \sim$ below 10^{-90} cm^2.

Best experiments are ~ 50 orders of magnitude away. This is hopeless, [but fortunately these detectors are not designed for that].

One would need a different type of dark matter and new tools to be able to detect gravitational strength interaction. This talk is a collection of some ideas in this direction.

Neutral "portals" to the SM – an organizing principle

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda\, S^2 + A\, S)$ Higgs-singlet scalar interactions

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^{\,i} A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^{\,i} A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^{\,A}\ \partial_\mu a / f_a$ axionic portal

……….

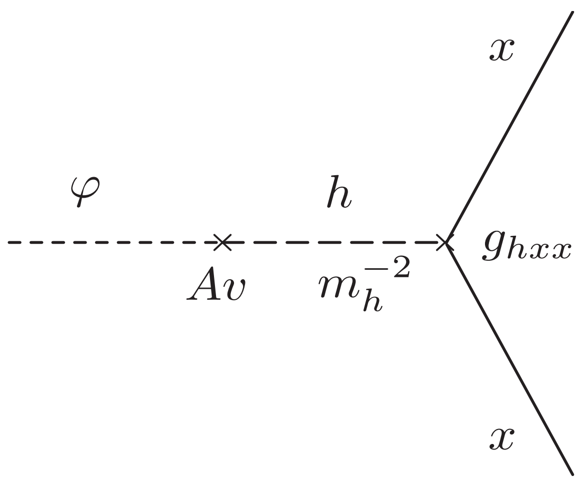
$$\mathcal{L}_{\rm mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\rm med}^{(k)} \mathcal{O}_{\rm SM}^{(l)}}{\Lambda^n},$$

Scalar DM through super-renormalizable portal

- Piazza, MP, 2010: *There is a unique portal in the SM*

$$V = -\frac{m_h^2}{2} H^\dagger H + \lambda (H^\dagger H)^2 + \underline{A H^\dagger H \phi} + \frac{m_\varphi^2}{2}\phi^2 \,.$$

- There is no runaway direction if $A^2/m_\varphi^2 < 2\lambda$
- After integrating out the Higgs, the theory becomes very similar to Brans-Dicke – but *better* because of UV completeness of our theory.



$$g_{\varphi xx} = \frac{Av}{m_h^2} g_{hxx}$$

$$g_{hNN} \simeq \frac{200 - 500\,\mathrm{MeV}}{v} \sim O(10^{-3})$$

- Main consequence of such model is a new scalar force mediated by a light field.

Super-cool Dark Matter from misalignment

Sub-eV mass ranges – has to be non-thermal.

- QCD axion (1981- onwards).

…

- Scalar DM through the super-renormalizable Higgs portal (Piazza, MP, 2010) Also, pointed out dark photon DM possibility.
- Nelson, Scholtz (2011); Arias et al (2012); Jaeckel, Redondo, (2013); … J Mardon et al, (2014).
- Most models are subject to uncertainty related to the "initial displacement" of the field from minimum (and possible isocurvature perturbation constraints.)
- Sad part*: for non-QCD axion models, signals are not guaranteed, because nothing requires this DM to be coupled to the SM*

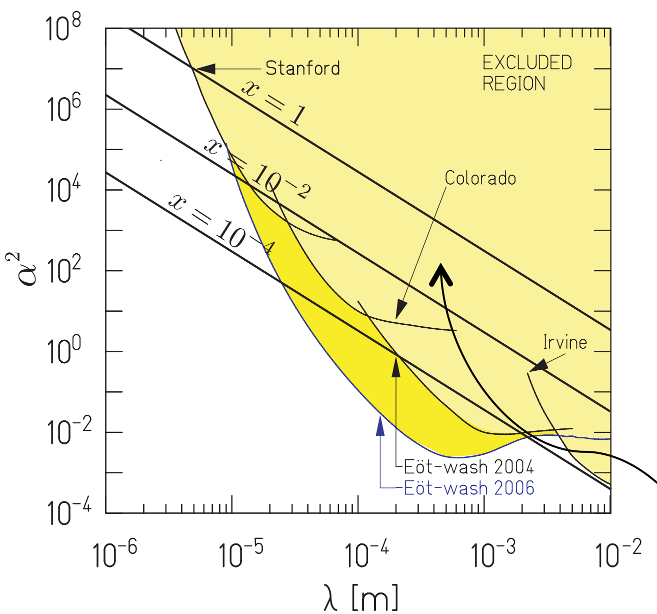
5^{th} force from Dark Matter exchange

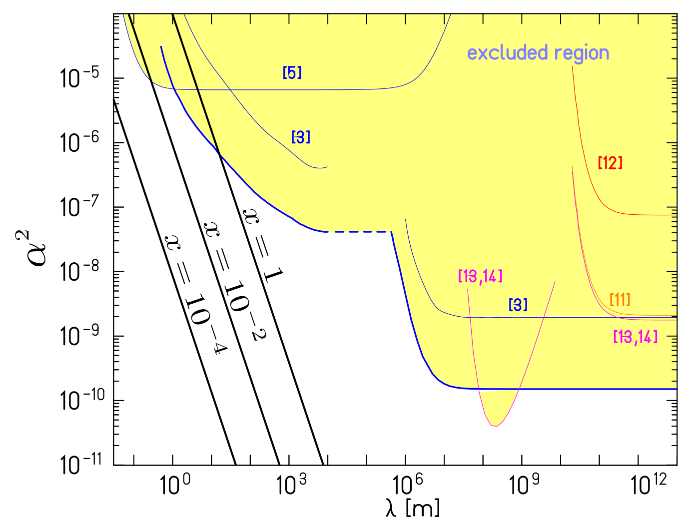
- The main observational consequence of this model: possibility to have an observable 5^{th} force (x= A/mass)
- For the traditional parametrization, $V(r) = -G\frac{m_A m_B}{r}(1 + \alpha_A \alpha_B\, e^{-m_\varphi r})\,.$

we can derive the strength of coupling

$$\alpha = g_{hNN}\frac{\sqrt{2}M_P}{m_{\rm nuc}}\frac{Av}{m_h^2}$$
$$\simeq 10^{-3}\left(\frac{m_h}{115\,\mathrm{GeV}}\right)^{-2}\frac{A}{10^{-8}\mathrm{eV}}.$$

(! *the second bracket* = 0.83)





One can expect a “natural” 5^{th} force from DM in 10 micron – 100 m range

Extended field configurations of light fields

Take a simple scalar field, give it a self-potential e.g. $V(\phi) = \lambda(\phi^2 - v^2)^2$.

If at x = - infinity, $\phi = -v$ and at x = +infinity, $\phi = +v$, then a stable *domain wall* will form in between, e.g. $\phi = v \tanh(x\, m_\phi)$ with

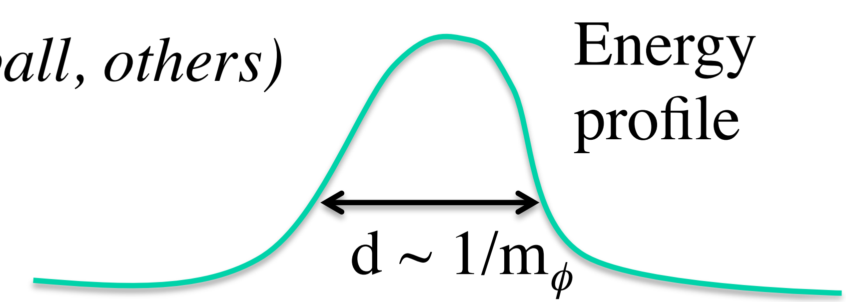
$m_\phi = \lambda^{1/2} v$

The characteristic "span" of this object, $d \sim 1/m_\phi$, and it is carrying energy per area $\sim v^2/d \sim v^2 m_\phi$ Network of such topological *defects* (TD) can give contributions to dark matter/dark energy.

0D object – a *Monopole (also a Q-ball, others)*

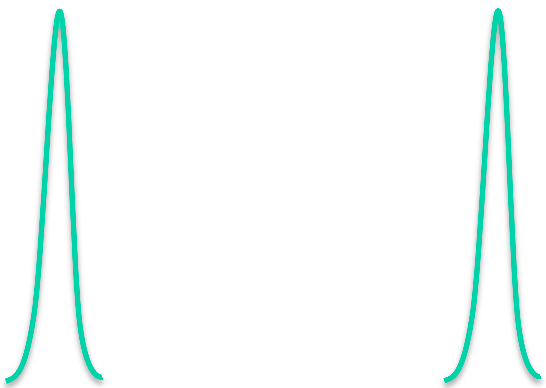
1D object – a *String*

2D object – a *Domain wall*

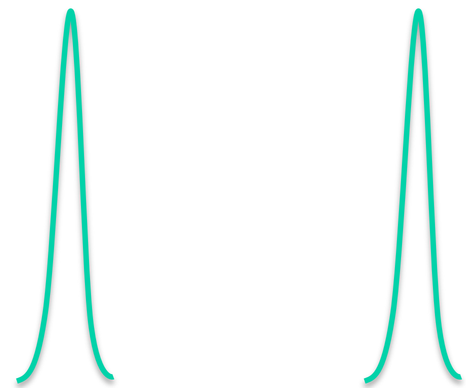


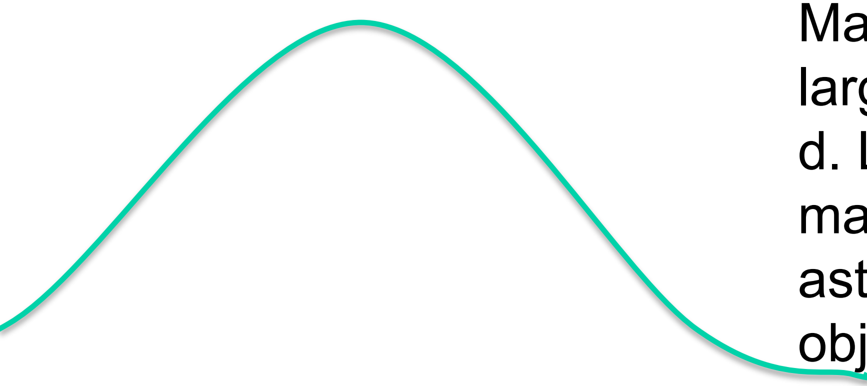
Naïve comparison with WIMPs and axions

Axions – small amplitude but “no space” between particles



WIMPs – EW scale lumps of energy (>> axion amplitude), very concentrated in space. And with significant ~ cm gaps between particles





Macroscopic DM – large amplitude but also large (possibly macroscopic) spatial extent d. Large compared to WIMPs individual mass, and then large (possibly astronomical) distances between DM objects.

Macroscopic DM is a possibility for DM that will have very different signatures in terrestrial experiments.

Possible Interactions

Let us call by ϕ, ϕ_1, ϕ_2, … - real scalar fields from TD sector that participate in forming a defect. (More often than not more than 1 field is involved). Let us represent SM field by an electron, and a nucleon.

Interactions can be organized as "*portals*": coeff $\times$ $O_{dark}O_{SM}$.

A. $$\frac{\partial_\mu \phi}{f_a} \sum_{\text{SM particles}} c_\psi \bar{\psi}\gamma_\mu\gamma_5\psi \quad \text{axionic portal}$$

B. $$\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi}\psi \quad \text{scalar portal}$$

C. $$\frac{\phi_1^2 + \phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi}\psi \quad \text{quadratic scalar portal}$$

D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi}\gamma_\mu\psi \quad \text{current} - \text{current portal}$$

An atom inside a defect will have addt'l contributions to its energy levels

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B. $\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi}\psi$ scalar portal — Shift of ω + extra gr. force

C. $\frac{\phi_1^2 + \phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi}\psi$ quadratic scalar portal — Shift of ω + extra gr. force

D $\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi}\gamma_\mu\psi$ current – current portal — extra gr. force

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A. $$\frac{\partial_\mu \phi}{f_a} \sum_{\text{SM particles}} c_\psi \bar{\psi}\gamma_\mu\gamma_5\psi \quad \text{axionic portal}$$ $f_a > 10^9$ GeV (astro)

B. $$\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi}\psi \quad \text{scalar portal}$$ $M_* > 10^{21}$ GeV (5^{th} force)

C. $$\frac{\phi_1^2 + \phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi}\psi \quad \text{quadratic scalar portal}$$ $M_* > 10^4$ GeV (5^{th} force+ast)

D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi}\gamma_\mu\psi \quad \text{current} - \text{current portal}$$ $M_* > 10^4$ GeV (5^{th} force+ast)

An atom inside a defect will have addt'l contributions to its energy levels

Transient signals from macroscopic DM

Regardless of precise nature of TD-SM particles interaction it is clear that

1. Unlike the case of WIMPs or axions, most of the time with TD DM there is no DM objects around – and only occasionally they pass through. Therefore the DM signal will [by construction] be *transient* and its duration given by $\sim$ size/velocity.

2. If the S/N is not large, then there can be a benefit from a network of detectors, or co-located detectors searching for a correlated in time signal.

3. There will be a plenty of the constraints on any model of such type with SM-TD interaction, because of additional forces, energy loss mechanisms etc that the additional light fields will provide.

Galactic DM

- Known things:

Approximate mass density: ~ 0.3 GeV / cm^3 (or 0.008 Solar masses/pc^3) near Solar system.

Velocity ~ 200 km/sec (~ 1/1500 of c, comparable to the virialized velocities of stars)

- Unknown things:

mass (distribution over mass), size, strength of interaction *on top* of gravitational one *if any*.

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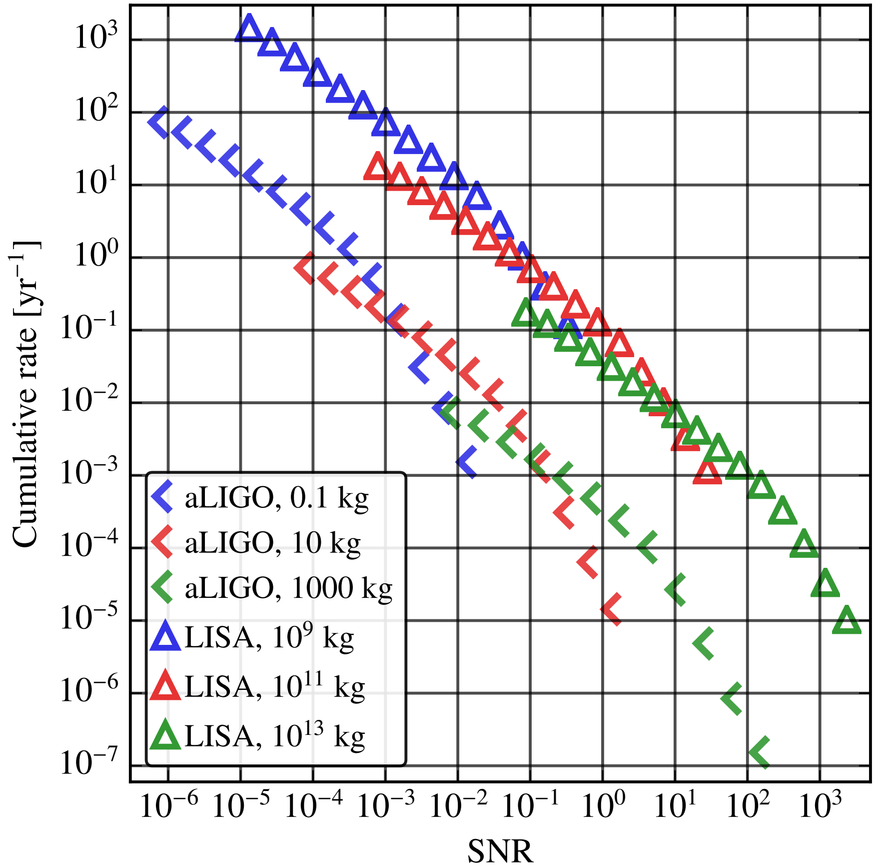
Inverse time for crossing a LIGO arm ~ 50 sec^{-1}. Inside the sensitivity range.

- Unknown things:

mass (distribution over mass), size, strength of interaction *on top* of gravitational one *if any*.

Let's take size → 0, vary mass and quantify sensitivity to gravitational interaction

Simulation of sensitivity to grav interaction

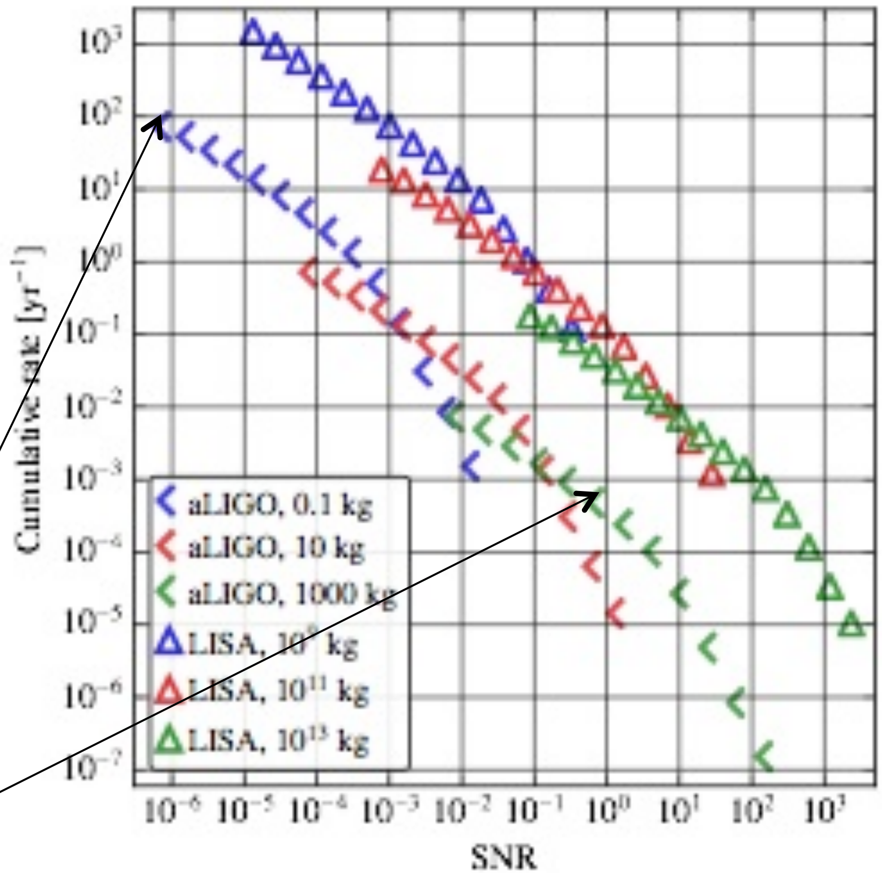


1606.01103

A passage of 0-dim objects (e.g. "monopoles") gives a disturbance signal with characteristic $\omega \sim v/L \sim 100$ Hz (a good range for Ligo!). Average energy density is fixed to galactic $\rho_{\rm DM}$.

A few orders of magnitude short from being able to detect gravitational-size interaction with macroscopic DM.

Simulation of sensitivity to grav interaction



- Hundred events per year correspond to SNR ~ 10^{-6} at LIGO. Alternatively SNR ~ O(1) events would occur at 1 per 1000 yr.
- LISA will do ~ two orders of magnitude better (for larger masses).
- *This is not hopelessly far away! (as for direct detection of WIMPs)*

Previously, this idea was studied in the context of primordial (small-ish) black holes, and space-based interferometers:

N Seto, A Cooray, PRD 2004

A Adams and J Bloom, astro-ph/0405266

Recent studies of macroscopic objects vs LIGO are in e.g.

Jaeckel, Khoze, Spannowsky, 1602.0391

Also in

Flambaum, Stadnik, 2014

Sensitivity to new Yukawa interaction

- We maintain small size, and introduce a non-gravitational interaction between DM and SM parametrized by a long-range Yukawa force,

- $V_{atom1\text{-}atom2} = - G_N m_1 m_2 /r \ (1 + \delta_{SM}^2 \mathrm{Exp}[-r/\lambda])$
- $V_{atom\text{-}DM} = - G_N m_{atom} m_{DM} /r \ (1 + \delta_{SM}\delta_{DM} \mathrm{Exp}[-r/\lambda])$

- We can try to UV complete this interaction by the same Higgs portal, $\phi\,(H^+H)$, and new Yukawa interaction in the dark sector, $\phi\bar{\psi}\psi$, where macroscopic DM is made for example out of "same sign" fermions ψ.

Sensitivity to new Yukawa interaction

- From the 5th force measurements and/or tests of GR we will know that the extra SM couplings are small, $\delta_{SM}^2 < 10^{-5}$. In contrast, the coupling to the dark sector can be large, $\delta_{DM} >> 1$ if the range of the force is much smaller than the galactic size (e.g. $\lambda \sim$ few km).
- Calculating the self-interaction DM-DM transport cross section we get

$$\sigma_{\text{DM-DM}} = 16\pi \times \frac{G_N^2\, M_{\text{DM}}^2\, \delta_{\text{DM}}^4}{v_{\text{DM}}^4} \times \log\left[\frac{\lambda}{r_{\text{DM}}}\right].$$

- If we apply existing bounds from self scattering, $\sigma/m < 1\ \text{cm}^2/\text{g}$, we arrive at

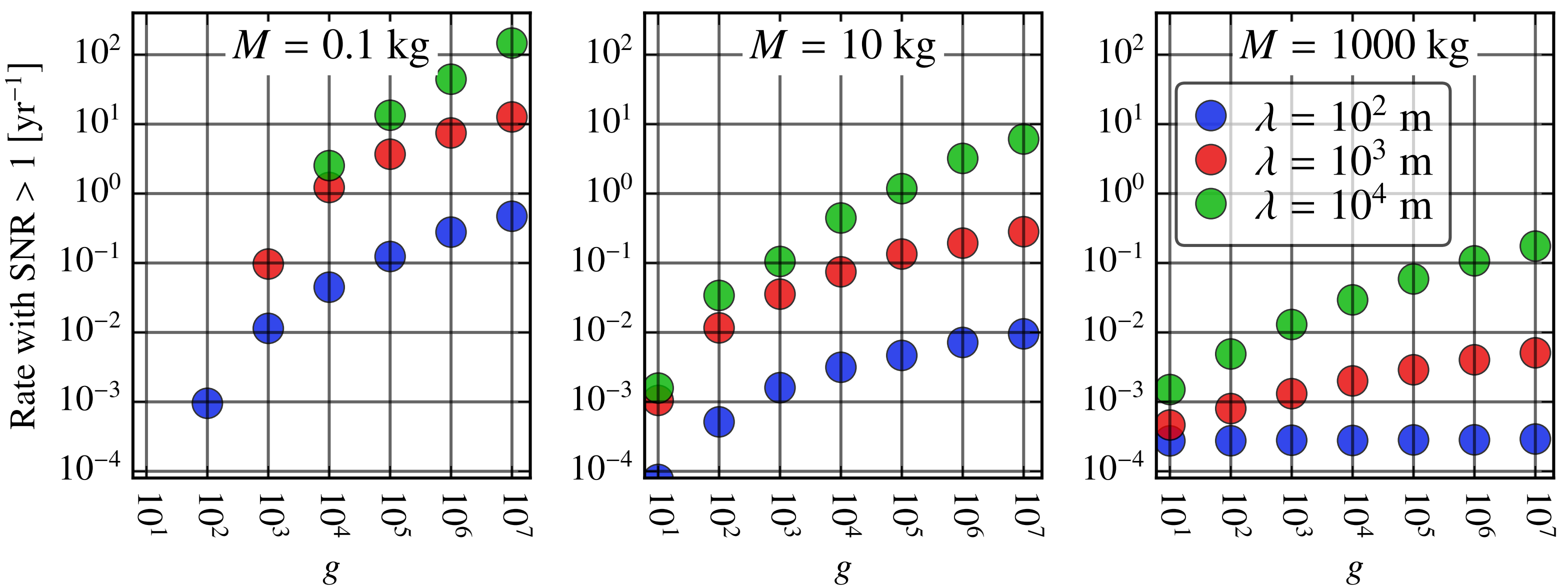
$$|\delta_{\text{DM}}| \lesssim 5 \times 10^9 \times \left(\frac{1\ \text{kg}}{M_{\text{DM}}}\right)^{1/4}.$$

- *There is a plenty of room for having* $\delta_{SM}\delta_{DM}$ *as large as* 10^7.
- "Self-organizing" dark matter could saturate the bound.

Sensitivity to new Yukawa interaction

- $g = \delta_{SM}\delta_{DM}$

aLIGO

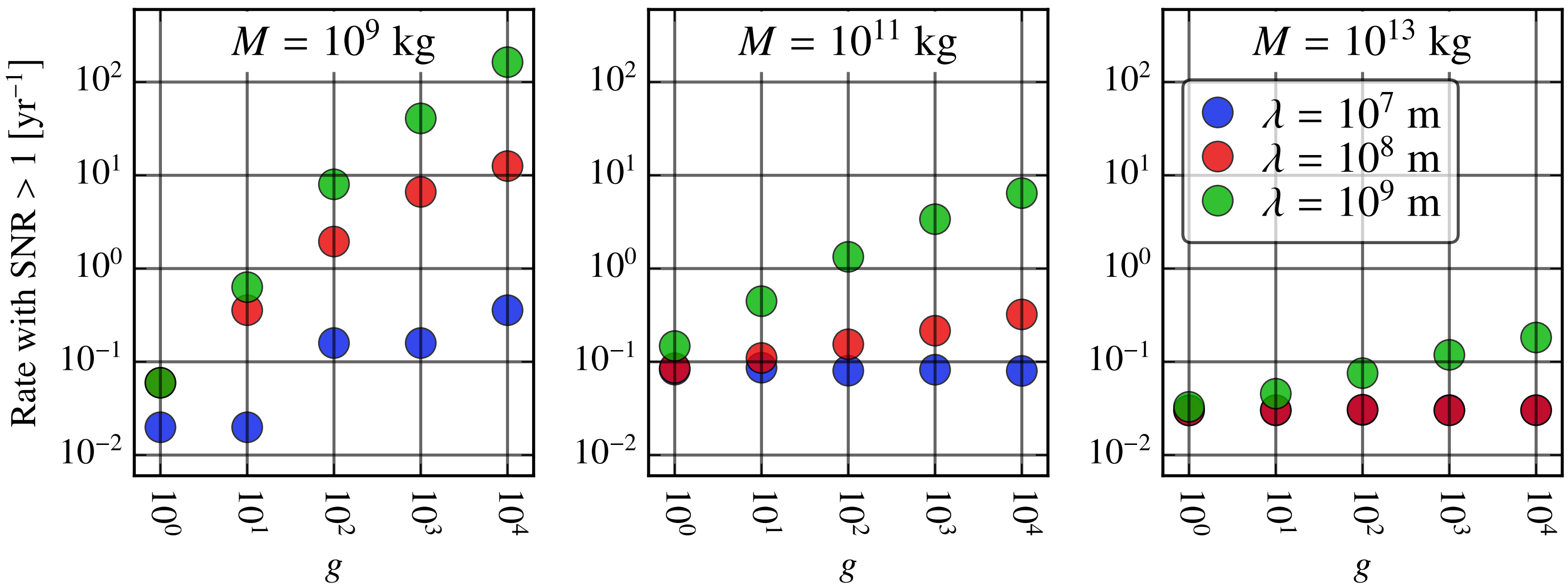


Maximal g of 10^7 can result in O(100) signal events at aLIGO.

Sensitivity to new Yukawa interaction

- $g = \delta_{SM}\delta_{DM}$

LISA



LISA event rate could be huge!

Ideas for separatinging signal from accidental background

- Unless the nature is "kind" and DM has some component in the form of domain walls (or extended objects with sharp boundaries) which is then going to be registered by all detectors, 0-dim objects are likely to "miss" other detectors. Difficult to tell apart from accidental spikes.
- Co-located detectors (like in the original LIGO plans) will help to reduce the accidental backgrounds.
- If the detectors are running continuously, and the event rate is large, >> 100/yr, one can start studying seasonal modulation (larger flux of DM due to constructive addition of Earth and Sun velocity in the summer).
- Large statistics may reveal some correlations that background may not have (DM passage has correlated amplitude and the inverse passage time).
- *Statistics of isolated spikes at LIGO needs to be studied.*

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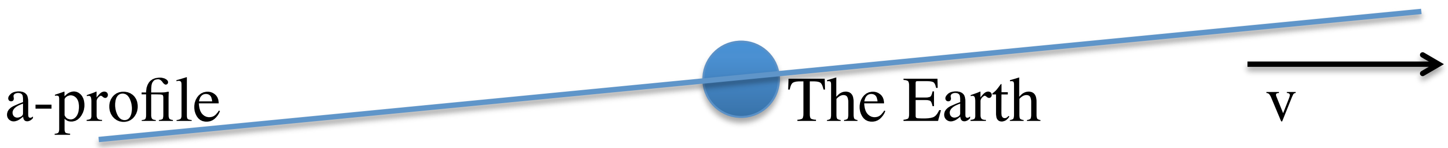
D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi}\gamma_\mu\psi \quad \text{current} - \text{current portal}$$ extra gr. force

An atom inside a defect will have addt'l contributions to its energy levels

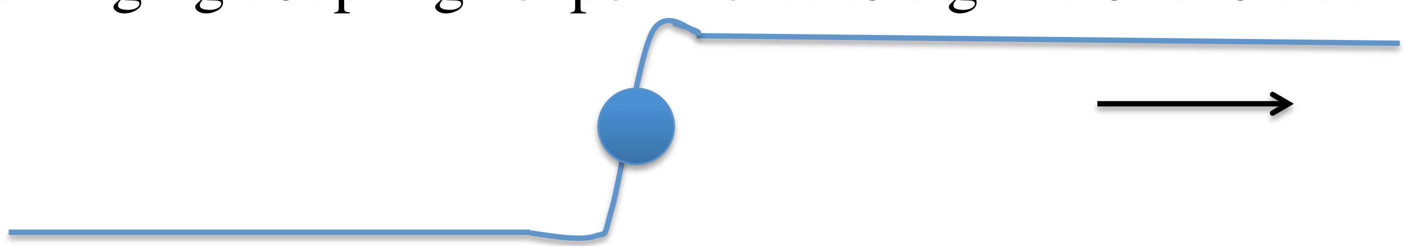
"transient LV" and "transient $\Delta\alpha/\alpha$ "

Typical "LV" experiment looks for $b_\mu \bar{\psi} \gamma^\mu \gamma_5 \psi$
that one can generalize as interaction os a spin i to with the *fixed* gradient of the scalar field a, $f_i{}^{-1} \partial_\mu a \bar{\psi}_i \gamma_\mu \gamma_5 \psi_i$



Similarly, existing terrestrial checks of $\boldsymbol{\Delta\alpha/\alpha}$ etc look for a smooth $d\alpha/dt$ signal, that is a *constant in time*.

And of course TD transient signal can be viewed as generalization of LV and "changing coupling" experiments to signals of short duration.



Signal of axion-like domain wall

Consider a very light complex scalar field with Z_N symmetry:

$$\mathcal{L}_\phi = |\partial_\mu \phi|^2 - V(\phi); \quad V(\phi) = \frac{\lambda}{S_0^{2N-4}} \left| 2^{N/2} \phi^N - S_0^N \right|^2$$

Theory admits several distinct vacua, $\phi = 2^{-1/2} S \exp(ia/S_0)$

$$S = S_0; \;\; a = S_0 \times \left\{ 0; \; 2\pi \times \frac{1}{N}; \; 2\pi \times \frac{2}{N}; \ldots \; 2\pi \times \frac{N-1}{N} \right\}$$

Reducing to the one variable, we have the Lagrangian

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - V_0 \sin^2 \left(\frac{Na}{2S_0} \right)$$

that admits domain wall solutions

$$a(z) = \frac{4S_0}{N} \times \arctan\left[\exp(m_a z)\right]; \quad \frac{da}{dz} = \frac{2S_0 m_a}{N \cosh(m_a z)}$$

$$\rho_{\mathrm{DW}} \leq \rho_{\mathrm{DM}} \Longrightarrow \frac{S_0}{N} \leq 0.4 \text{ TeV} \times \left[\frac{L}{10^{-2} \text{ ly}} \times \frac{\text{neV}}{m_a} \right]^{1/2}$$

If on top of that a-field has the axion-type couplings, there will be a magnetic-type force on the spin inside the wall, $H_{\mathrm{int}} = \sum_{i=e,n,p} 2 f_i^{-1} \nabla a \cdot \mathbf{s}_i$

Network of Magnetometers

- For alkali magnetometers, the signal is

Exper. Sensitiv.

S ~ below fT/√Hz

MP et al, PRL 2013

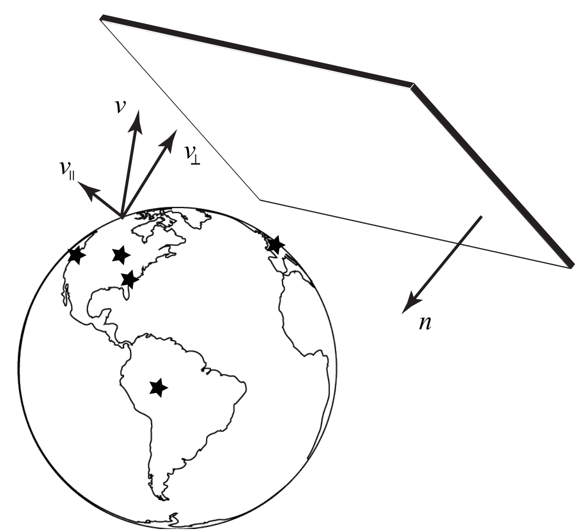
$$\mathcal{S} \simeq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \frac{S_0/N}{0.4\,\mathrm{TeV}} \times \left[\frac{m_a}{\mathrm{neV}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2}$$

$$\leq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \left[\frac{L}{10^{-2}\ \mathrm{ly}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2},$$

- For nuclear spin magnetometers, the tipping angle is

$$\Delta\theta = \frac{4\pi S_0}{v_\perp N f_{\mathrm{eff}}} \simeq 5\times 10^{-3}\,\mathrm{rad}\times\frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}}\times\frac{10^{-3}}{v_\perp/c}\times\frac{S_0/N}{0.4\,\mathrm{TeV}}$$

- It is easy to see that one would need >5 stations. 4 events would determine the geometry, and make predictions for the 5th, 6th etc…



* *Nobody has ever attempted this before*

Possible signature with atomic clocks

A. Derevianko, MP arXiv:1311.1244

Consider an operator $\frac{\phi^2}{M_*^2} m_e \bar{e} e$ that "renormalizes" the mass of an electron once an atom is inside a TD. Because of the quadratic nature of the coupling M_* can be quite low and at a ~ TeV. (There is a huge issue with naturalness of light ϕ, as always]

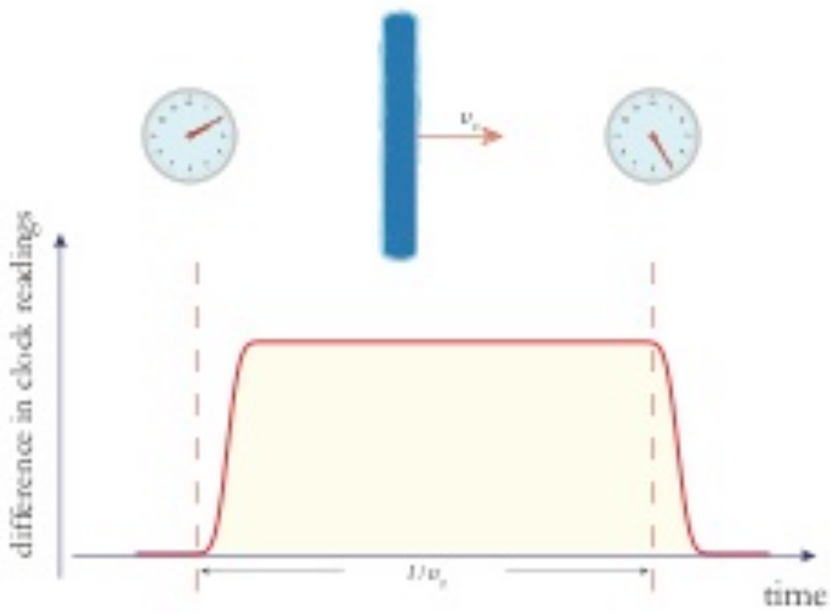
- The atomic frequencies will shift – temporarily – and in a different way for e.g. clocks on optical and microwave transitions.

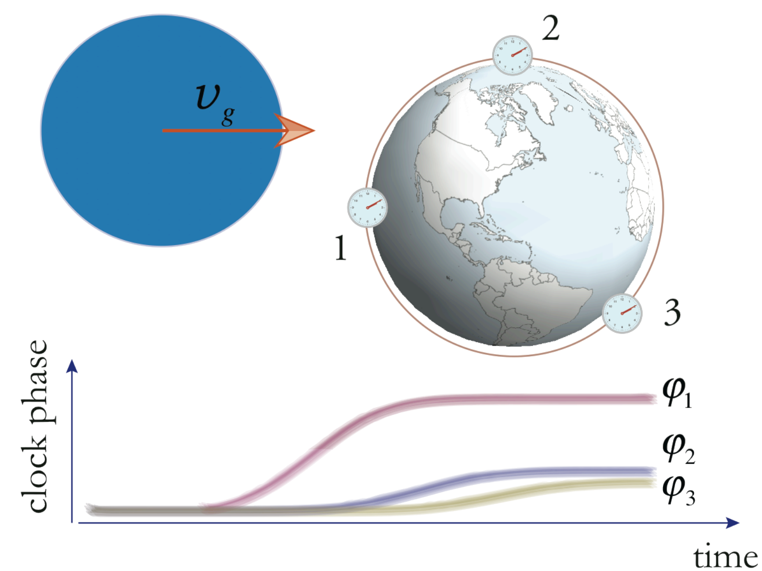
- If the $\delta\omega/\omega$ is shifted very briefly, current searches of $d\alpha/dt$ will not catch it as they integrate over a long time.

- Achieving sensitivity to $\delta\omega/\omega$ (1 sec crossing) ~ 10^{-14} seems possible, which will translate to M_* ~ 10^{12} GeV sensitivity.

- Quadratic scalar portal is the most promising

$$-\mathcal{L}_{\text{int}} = a^2 \left(\frac{m_e \bar{e} e}{\Lambda_e^2} + \frac{m_p \bar{p} p}{\Lambda_p^2} + \frac{1}{4\Lambda_\gamma^2} F_{\mu\nu}^2 + \ldots \right)$$





- Specific signatures will depend on the dimensionality of the defect and its size.

Experimental developments [old slide]

- First steps towards creating the network of correlated atomic magnetometers have been made with potential nods at Berkeley, Mainz, Cal State East Bay, Krakow… (Budker, Jackson Kimball, Gawlik, Pustelny and others). A multi-node magnetometer network is called **GNOME** collaboration.
- Atomic clock networks already exist (e.g. GPS, GLONASS etc). However, their sensitivity to a possible transient signal is not quantified properly. Blewitt, Derevianko, Roberts (UNR) are addressing that.
- Some of the atomic clocks will be include into GNOME network.

Conclusions

1. Dark matter takes 25% of the Universe's energy budget. Its identity is not known. Many theoretical possibilities for the CDM exist: WIMPs, super-WIMPs, coherent scalar fields etc.

2. **It is important to cast as wide an experimental net as possible*, as we continue our investments in WIMP searches* Analysis of precision physics data (e.g. 5^{th} force searches) may reveal the presence of new light fields.

3. *Macroscopic* dark matter can induce transient signals.

4. Gravitational wave interferometers can be used to directly search for 200km/sec galactic objects. Saturating DM abundance, at LIGO one falls a few orders of magnitude short from being sensitive to gravitational pull of passing O(kg) size objects. New type of forces, such as e.g. Yukawa force can be probed in the relevant part of parameter space.

5. Statistics of isolated spikes at LIGO is of great interest!